A STUDY OF TECHNIQUES FOR REDUCING ASH DEPOSITION IN COAL-FIRED GAS TURBINES

Ronald G. Logan, George A. Richards,
Charles T. Meyer, and Rodney J. Anderson
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, WV 26505

INTRODUCTION

Corrosion and deposition on engine components are potential barriers to the utilization of coal and coal-derived fuels in heat engines. The U.S. Department of Energy has established a program to study mechanisms of ash deposition, with the goal of developing methods to alleviate deposition problems in coal-fired gas turbines. Ash deposits are formed in the turbines by the adherence of ash particles to the surfaces of stators and blades. During combustion, components of the coal ash become molten and thus readily adhere to metal surfaces in the turbine upon impaction (Figure 1) [1]. Deposit growth can be enhanced by the formation of a liquid layer on the surface of the ash particles, which may consist of alkali sulfates, aluminosilicates, or low-melting compounds of iron or calcium [2-5]. Typically, some fraction of the total amount of ash (denoted as the sticking coefficient [6,7]) actually sticks to turbine components forming a deposit.

The tendency of various coals to form ash deposits during combustion is a function of several variables including the ash chemistry, the gas temperature and pressure, the gas velocity, and the temperature of the turbine components. The objective of this work was to measure the sticking coefficient of various coals while studying the basic mechanisms of ash deposit formation to facilitate the development of techniques for preventing deposition in coal-fired gas turbines. Two methods of mitigating ash deposition were studied; active cooling of the deposition target, and the use of fuel additives. Surface cooling has been shown to be effective at reducing ash deposition in boilers [8] and in tests in gas turbine simulators [9]. Deposition reduction can also be accomplished by the use of fuel additives. The injection of additives which can promote spalling of weakly bonded ash has been used in boilers to reduce deposit strength [8]. It has been proposed that additives can act as getters for vapor phase alkali [10] to prevent the formation of low-melting alkali sulfates which can act as a glue to increase deposition. The additives may also contribute to the erosion of ash deposits. Spiro et al. [11] have reported the successful use of kaolin clay to reduce deposition problems in a gas turbine simulator.

EXPERIMENTAL

Experiments were performed in an electrically heated, laboratory scale drop-tube combustor designed to operate at temperatures up to 1500 C and pressures up to 12 atmospheres. This combustor, the combustion/deposition entrained reactor (CDER), is shown in Figure 2. The reaction zone in the CDER is 50.8 cm long and 5.1 cm in diameter. The residence time of coal particles in the reaction zone is approximately 500 ms. Approximately 3 grams per hour of -400 mesh pulverized coal was entrained in air from a circulating feeder, and injected into the reactor with a total air flow rate of 30 slpm. These fuel and air flow rates resulted in a relatively low equivalence ratio of 0.015, compared to overall equivalence ratios of approximately 0.3 in gas turbines. However, deposition characteristics were shown to be independent of equivalence ratio for coal feed rates varied over an order of magnitude. The coal feed rate used in these experiments allowed longer sampling times which increased the ease and consistency of the measurements.

At the exit of the reaction zone the products of combustion were accelerated through a 3.2 mm diameter nozzle, creating a jet which impinged on a flat platinum disk at approximately 300 m/s, similar to the gas velocity expected in the first stage of a gas turbine. At this velocity, a stagnation flow configuration was created such that all particles greater than 0.5 microns in diameter impacted on the target, as would occur on the leading edge of a gas turbine blade. The 12.7 mm diameter platinum targets were positioned approximately 6 mm below the nozzle aperture. The nozzle and target configuration are shown in Figure 3. Platinum was used as a target material because of its inertness, thereby eliminating surface reactions peculiar to a specific blade material which could effect the experimental results. The target surface was cooled from the underside by introducing an opposing jet of cooling air. Thus the targets could be cooled over a range of temperatures by varying the cooling air flow rate. The target temperature was measured throughout each test via a two-color optical pyrometer monitoring the backside of the platinum target.

The reactor is equipped with three sets of optical access ports for use with a variety of nonintrusive diagnostic instrumentation that is currently under development. An on-line mass spectrometer was used to monitor the major components of the exhaust. A more detailed description of the CDER and its associated instrumentation has been presented previously [12].

Sticking coefficients were determined by first passing the jet of gas and ash particles through a filter to determine the total mass arrival rate. A vacuum pump was used to draw the gas through the filter, which was positioned in the same location as the target. Then a target of known weight was inserted in the jet and a deposit was collected for a specified period of time, usually 10 minutes. The sticking coefficient was calculated as the ratio of the weight gain of the target to the total mass arriving at the target (determined by the filter sample). The filter samples were quenched with cold air, resulting in unburned carbon in the samples. Since carbon was burned out of the deposits, filter samples were analyzed for carbon content to correct the ash arrival rate used to calculate the sticking coefficient.

The adhesion strength of the ash deposits was measured with an in situ adhesion strength meter (ASM). The ASM (shown in Figure 4) consists of a quartz load cell connected to a linear actuator. Attached to the linear actuator is a ceramic probe mounted on a rotational stage for precise control of the probe position. The entire unit is mounted on a precision translation stage, and the probe is coupled directly to the CDER for in situ measurements. When pressure is applied to an ash deposit via the probe, the load cell measures the shear force required to break the deposit free from the platinum target at the temperature of the reactor.

RESULTS

The baseline coal used in this study was Arkwright Pittsburgh bituminous. In addition, a highly-cleaned Kentucky Blue Gem bituminous coal was also studied.

Chemical analyses of the Arkwright and Blue Gem coals are shown in Table 1. All data reported here were collected at atmospheric pressure. Results from tests utilizing target cooling for ash deposition mitigation showed that at lower combustion (exhaust gas) temperatures (1100 C), target cooling had no effect on the sticking coefficient. However at higher combustion temperatures (1300 C), target cooling produced a significant reduction in the fraction of adhering ash (Figure 5). Sticking coefficients were higher at 1100 C and deposits were granular in character and easily removed. Deposits collected at 1300 C, although smaller, were tightly bonded to the target surface. Scanning electron microscope particle size analyses of ash samples collected at the two combustor temperatures showed that the high temperature combustion produced ash particles less than 20 microns in diameter, with a peak in the mass distribution of approximately 5 microns. Conversely, a large fraction of the low temperature ash was concentrated in the particle sizes between 10 and 40 microns. Only a small fraction of the ash was contained in particles smaller than 5 microns. It was proposed that target cooling was effective at reducing deposition at the higher combustion temperatures because the smaller particles were more easily cooled in the boundary layer above the cooled surface, which effectively froze the molten phases in the particles. The larger particles produced at the lower combustion temperature arrived at the target unaffected by the cooled surface. The data suggest that a proper combination of combustion history and hardware surface temperature can contribute to effective deposition mitigation if the combustion process is tailored to produce fine ash particles. A detailed discussion of these results has been presented elsewhere [13].

Three additives were tested; limestone and tricalcium silicate (potential sulfur sorbents), and koalin. These additives were ground to -400 mesh and mixed with the coal prior to combustion in the CDER. Figures 6 and 7 show the effects of the addition of various amounts of kaolin on the sticking coefficient of Arkwright coal at 1100 and 1300 C, respectively. The data in Figure 6 show that the addition of kaolin had no effect at a reactor temperature of 1100 C until the amount of added kaolin roughly equaled the weight per cent of ash in the coal. Target surface cooling was ineffective at reducing the sticking coefficient at any percentage of kaolin addition for a reactor temperature of 1100 C, as was the case with the Arkwright coal alone. Figure 7 shows the results of similar tests conducted at a reactor temperature of 1300 C. At this temperature, the effectiveness of kaolin addition was more pronounced. Increasing percentages of kaolin decreased the sticking coefficient, and further, kaolin addition enhanced the mitigating effect of target cooling. In fact, the sticking coefficient measured with 7.5 percent kaolin addition and maximum target cooling was the lowest recorded for the Arkwright coal under any reactor conditions or with any other additive tested. This sticking coefficient was approximately an order of magnitude lower than that of the Arkwright coal alone with cooled targets and approximately two orders of magnitude lower than Arkwright alone with no cooling of the target surface.

Limestone addition reduced the sticking coefficient by an order of magnitude at a reactor temperature of 1100 C, and to a lesser degree at a temperature of 1300 C (Figures 8 and 9). However, cooling the deposition target had no effect on the sticking coefficient at either reactor temperature. This is in contrast to results of tests with Arkwright coal only, and Arkwright plus kaolin which showed an order of magnitude reduction in sticking with target cooling at a reactor temperature of 1300 C. Tests with tricalcium silicate produced results similar to those for the limestone tests. Tricalcium silicate was more effective at 1100 C (Figure 10). At a Ca/S ratio of 4, the sticking coefficient was reduced approximately an order of magnitude, however there was no effect of target cooling. At a reactor temperature of 1300 C with Ca/S ratios less than 1.0, the deposition characteristics were similar to Arkwright coal only, showing an order of magnitude decrease with target cooling (Figure 11). However, mixtures with higher Ca/S ratios showed no reduction of sticking coefficient with target cooling.

The addition of kaolin substantially reduced the adhesion strength of the ash deposits. Many of the deposits collected during the kaolin tests fell off of the targets as they were removed from the CDER. Thus, the measure of the sticking coefficient alone may not adequately assess the effectiveness of kaolin addition for deposition reduction, since the fraction of ash that does adhere is easily removed. Kaolin may react chemically with components of the ash to produce a more friable deposit [10]. Deposits collected during limestone and tricalcium silicate addition lacked this feature, indicating that sticking coefficient reductions measured during these tests may have been due to deposit erosion.

CONCLUSIONS

In general, tricalcium silicate and limestone were marginally effective at reducing the sticking coefficient of the coal at the lower reactor temperature. Both additives tended to reduce the effectiveness of target cooling for lowering the sticking coefficient. Thus, while limestone addition lowered the sticking coefficient at 1300 C with no target cooling, the sticking coefficient was lower without the additive when the target was cooled. Kaolin was very effective at reducing both the sticking coefficient and the adhesion strength of the ash deposits, and produced the lowest sticking coefficient measured for the baseline coal. The data showed that the proper combination of gas temperature, surface temperature, and additive can be an effective means of minimizing the detrimental effects of ash deposition in coal-fired gas turbines.

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1A:11-9-88:vw:5a

Coal Rank	Arkwright Pittsburgh Bituminous	Blue Gem (Cleaned) Bituminous
% ASTM Ash	6.93	0.56
Ash Comp. (Wt%)		
SiO_2	48.09	16.86
Al_2O_3	25.07	22.75
Fe_2O_3	10.95	29.57
TiO_2	1.27	1.95
P_2O_5	0.18	0.48
CaO	5.78	7.03
MgO	1.25	2.46
K_2O	1.16	0.53
Na_2O	0.90	1.54
SO_2	5.34	8.07
Ash Fusion Temp. (C) ($\pm$ 40)		
(ASTM, 1977)		
Initial Deformation	1,190	1,238
Softening	1,316	1,308
Hemispherical	1,356	1,371
Fluid	1,383	1,427

Table 1: Ash Characteristics

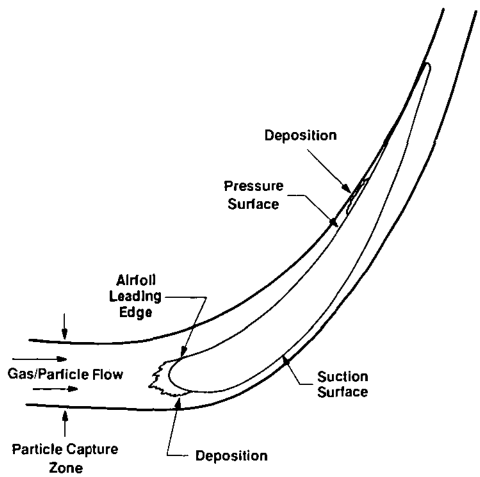
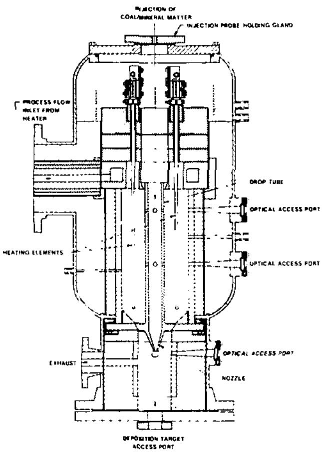


Figure 1: Particle Deposition on a Gas Turbine Vane

Item	Test Section
PRESSURE, ABSOLUTE, atm	1-12
FLOW RATE, scfh	25-700
VESSEL LENGTH, in	60
VESSEL OUTSIDE DIAMETER, in	24
WALL THICKNESS, in	3/8 (sch 40-304LSS)
PROCESS STREAM EXIT TEMPERATURE, °F	2,500
VESSEL SKIN TEMPERATURE, °F	< 300
ELEMENTAL TEMPERATURE (maximum), °F	3,000
HEATING ELEMENTS	KANTHAL SUPER 33 9/18
HEATER OUTPUT, watts	7,060
POWER SUPPLY, V/A	35/350
EXHAUST FLOW COMPOSITION	DILUTE COAL POC/ FILTERED
EXHAUST FLOW PRESSURE/TEMPERATURE	< 2 atm; < 400°F



TEST SECTION

Figure 2: CDER System Design Specifications

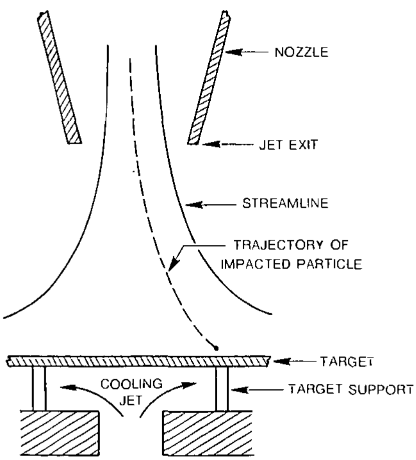


Figure 3: CDER Nozzle/Target Assembly

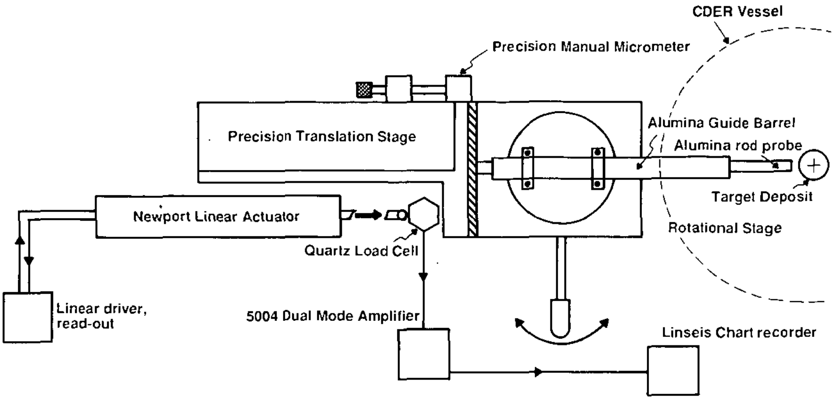


Figure 4: Adhesion Strength Meter (ASM)

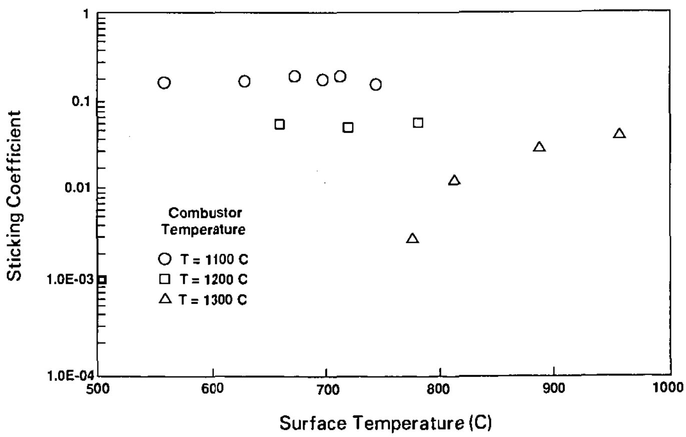


Figure 5: Effect of Target Cooling on Deposition; Arkwright Coal

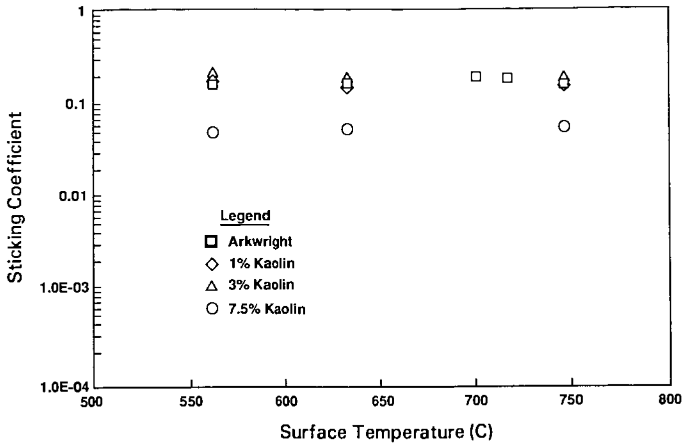


Figure 6: Effect of Target Cooling on Deposition; Arkwright Coal/Kaolin, T=1100 C

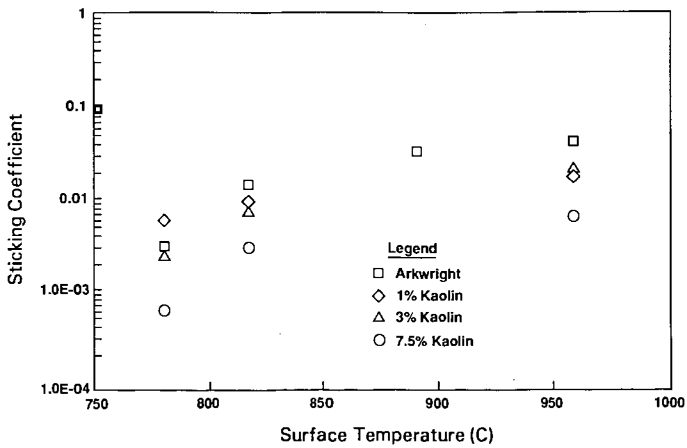


Figure 7: Effect of Target Cooling on Deposition; Arkwright Coal/Kaolin, T=1300 C

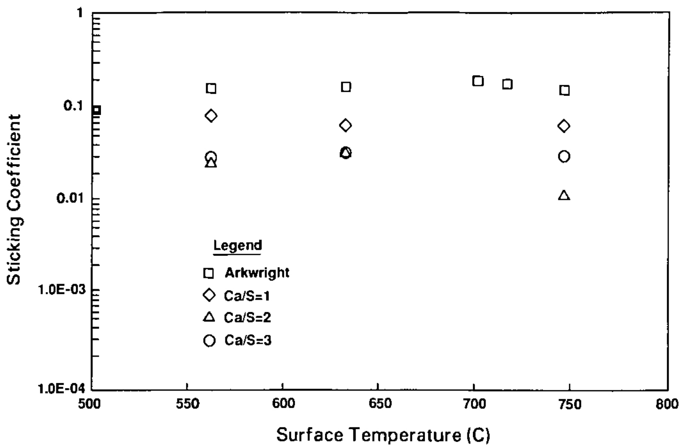


Figure 8: Effect of Target Cooling on Deposition; Arkwright/Limestone, T=1100 C

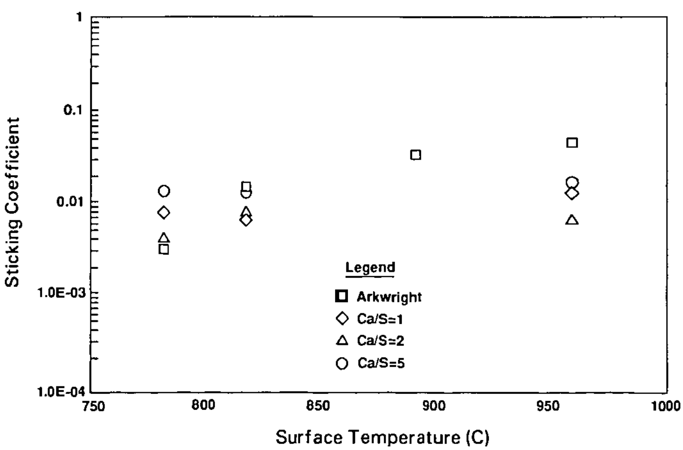


Figure 9: Effect of Target Cooling on Deposition; Arkwright/Limestone, T=1300 C

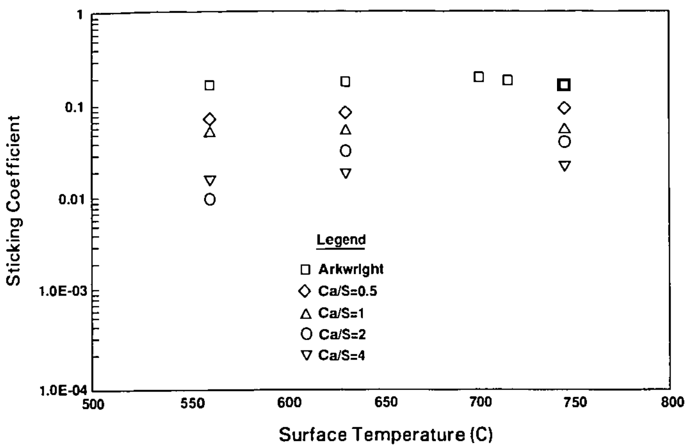


Figure 10: Effect of Target Cooling on Deposition; Arkwright/Tricalcium Silicate, T=1100 C

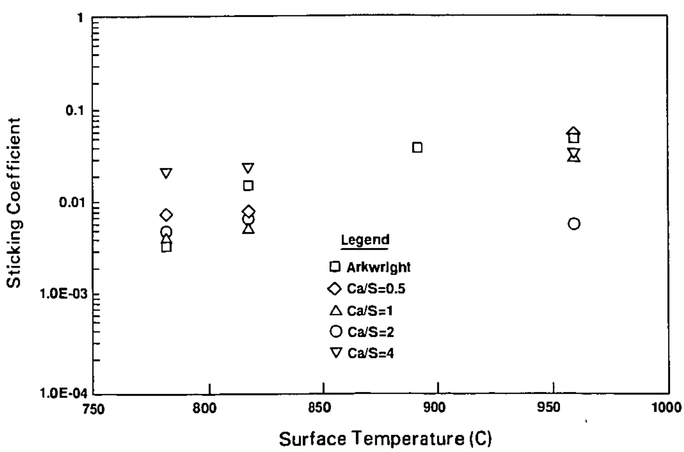


Figure 11: Effect of Target Cooling on Deposition; Arkwright/Tricalcium Silicate, T=1300 C